APPLICATION

OF

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FOR

UNITED STATES LETTERS PATENT

ON

SINGLE-FREQUENCY NARROW LINEWIDTH 1μM FIBER LASER

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ASSIGNED TO

NP Photonics, Inc.

SINGLE-FREQUENCY NARROW LINEWIDTH 1μM FIBER LASER

BACKGROUND OF THE INVENTION

5   Field of the Invention

This invention relates to fiber lasers and more specifically to a single frequency 1 μm fiber laser with narrow linewidth (<10 kHz) formed from ytterbium doped oxide-based multicomponent glasses.

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Description of the Related Art

Rare-earth doped glass fiber lasers were first proposed in the 1960s and have received considerable attention in the 1980s for potential applications in optical communication

15   (Michel J. F. Digonnet, "Rare-Earth Doped Fiber Lasers and Amplifiers," Marcel Dekker, New York 2001). For laser emission to occur, the active fiber is placed inside a resonant cavity. The optical feedback can be provided simply by the reflectivity of the end facets, by mirrors, by

20   distributed feedback Bragg (DFB) gratings, or by distributed Bragg reflectors (DBR), or by constructing a ring cavity structure. Laser emission occurs when the total gain overcomes the losses in the cavity. Hence, a minimum gain has to be achieved to reach the laser threshold condition.

25   Typical fiber lasers lase in a great number of longitudinal modes in single transverse mode optic fibers, the so-called single mode fibers. A single longitudinal mode (single frequency) fiber laser 1.55μm was demonstrated by Ball et al (G.A. Ball, W.W. Morey, W.H. Glenn, IEEE

30   Photonics Technology Letters, Vol. 3, No. 7, July 1991) utilizing two intracore Bragg reflectors for cavity feedback

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and longitudinal mode discrimination in a 50cm Er^{3+} doped silica fiber. US patent 5,305,335 to Ball describes single frequency Er^{3+} doped fiber laser consisting of a pair of Bragg reflectors separated by a 9cm cavity. U.S. Patent

5   5,237,576 to DiGiovanni describes a fiber laser of 5 cm or less using fluorine-phosphorous-doped silica matched index cladding, a germania-alumina-doped silica outer core and an alumina-erbium-doped silica inner core in which the DBRs are formed in the doped fiber. *W.H. Loh et al. Journal of*

10   *Lightwave Technology, Vol. 16, No.1, pp. 114-118 January 1998* describes a 1.5 cm phosphosilicate single-mode fiber lasers co-doped with Er:Yb. These lasers provide a $1.5\mu m$ single-frequency output of less than 1mW typically. A booster amplifier is required to produce output powers

15   greater than 10 mW. US patent 5,469,520 to Morey and US Patent 6,229,827 to Fernald describe tuning techniques using fiber Bragg gratings.

Other applications, such as, seeder lasers, LIDAR, optical heterodyne systems, nonlinear frequency conversion,

20   coherent satellite communication, and distributed sensing require a robust $1\mu m$ single frequency narrow linewidth fiber laser with output powers of at least 2 mW, preferably more than 20 mW. A $1\mu m$ wavelength is required to match the gain energy level of the widely used Nd:YAG laser crystal at

25   1.064 μm. Single-frequency operation with a linewidth less than 10 kHz provides both the resolution and long coherence needed by these applications. The $1\mu m$ laser should have sufficient output power without the need for a booster amplifier in order to maintain the high signal to noise

30   ratio.

Current $1\mu m$ single frequency narrow linewidth lasers

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are generated from solid state lasers using non-planar ring oscillators (NPROs) technology. US Patents 4,578,793 to Kane and 5,043,996 describe solid state monolithic nonplanar ring oscillators which can operate as unidirectional single-

5   frequency lasers in the presence of a sufficiently strong magnetic field.

Current 1μm fiber laser technology does not support such performance. Efficient single transverse mode 1μm ytterbium silica fiber lasers are described by *J.R. Armitage*

10   *et al Electronics Letters, Vol.25, No.5, 1989, pp. 298-299 and H.M. Pask et al Electronics Letters, Vol30, No.11, 1994, pp. 863-864.* M. Auerbach *et al Optics Communications, 195(2001) pp.437-441* reported a 1.6W 1μm ytterbium fiber laser with a spectral line width of 600MHz from a double-

15   clad silica fiber. 0.5mW Single-frequency 1μm ytterbium-doped silica fiber laser was achieved using 1.5 to 10 m long silica fiber stabilized by spatial hole burning by *R. Paschotta et al Optic Letters Vol. 22, No. 1, pp.40-42.* U.S. Patent 5,710,786 describes a 1μm pump source for

20   pumping ionized praseodymium for amplification of signals in the 1280 to 1340nm range. The pump source uses a silica-based glass double-clad optical fibre doped with triply ionized rare-earth ytterbium ions and fibre gratings formed therein. To efficiently pump the praseodymium, the pump

25   source output has a single spatial (transverse) mode at the laser wavelength of 1012 to 1022nm. U.S. Patent 5,991,314 to Ionov et al describes cladding pumped ytterbium fiber laser for pumping erbium doped fiber amplifiers. All these ytterbium fiber lasers were demonstrated in silica fibers.

30   It is very difficult if not impossible to demonstrate

high power single frequency narrow linewidth 1μm ytterbium silica fiber laser with the present state of the art. It is therefore an object of the presentation invention to provide a high power single frequency narrow linewidth 1μm fiber

5   laser.

SUMMARY OF THE INVENTION

The present invention provides a compact single frequency, single-mode 1μm fiber laser with narrow linewidth

10   (<10 kHz) and high output power (> 2mW and preferably >20 mW).

The 1um fiber laser is formed with an oxide-based multi-component glass fiber doped with triply ionized rare-earth ytterbium ions and fiber gratings formed in sections

15   of passive silica fiber and fused thereto. The multi-component glass supports higher doping concentrations, 0.5-30 wt. %, than silica fiber, hence higher output power levels in fiber lengths less than 5cm and preferably less than 3cm. Formation of the gratings in passive silica fiber

20   both facilitates splicing to other optical components and reduces noise thus improving linewidth. The use of a polarization maintaining (PM) fiber in the pump source further improves wavelength stability, linewidth and vibration/acoustic sensitivity.

25   In another embodiment, the gain fiber is a polarization maintaining (PM) fiber, which reduces the noise level in the laser and improves output power stability. As a result of their specific local environment, the active ions experience an anisotropy that leads to polarization

30   dependent gain, which means that the gain spectra for two different polarization components are not the

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same. Combining polarization selective feedback with a polarization maintaining active fiber reduces the low frequency noise that results from random polarization fluctuations inside the laser cavity.

5   These and other features and advantages of the invention will be apparent to those skilled in the art from the following detailed description of preferred embodiments, taken together with the accompanying drawings, in which:

10   BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a diagram of a single-frequency fiber laser in accordance with the present invention;

FIG. 2 is a plot of the absorption spectra of ytterbium doped glasses;

15   FIG. 3 is a diagram of the longitudinal mode spacing and grating bandwidth that produce a single-frequency output;

FIGs. 4a and 4b are plots illustrating single-frequency narrow linewidth performance and output power levels;

20   FIG. 5 is a sectional view of the gain fiber;

FIGs. 6a and 6b are diagrams of a packaged single-frequency fiber laser including temperature control and vibration isolation; and

FIG. 7 is a diagram of a pump source with a PM fiber.

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DETAILED DESCRIPTION OF THE INVENTION

The present invention provides a compact single frequency, single-mode 1μm fiber laser with narrow linewidth (<10 kHz) and high output power (>2mW and preferably >20

30   mW).

As shown in figures 1 through 4, a 1μm fiber laser **10**

is formed with an oxide-based multi-component glass single mode fiber 12 doped with triply ionized rare-earth ytterbium ions. Narrowband and broadband fiber gratings 14 and 16, respectively, are formed in sections of passive silica fiber 18 and 20 and fused to the ends of gain fiber 12 to form a resonant cavity that provides the feedback necessary to sustain laser operation. The reflectivity of the broadband grating 16 should be as close to 100% as possible. The reflectivity of the narrowband grating 14 is less than 100%, suitably 30-90% depending upon the pump power and target output power, such that power can be removed from the cavity. Alternately, the broadband grating could be used to output couple the laser energy.

Multi-component glasses support higher doping concentrations than silica glass, hence higher output power levels. The ytterbium doping concentration is 0.5-30 wt. % and typically 3-20 wt. %. The formation of the gratings in passive silica fiber rather than the gain fiber reduces ASE noise, which improves linewidth. As will be described with reference to figures 6 and 7, thermal stabilization and vibration isolation of the gain fiber and gratings and the use of a polarization maintaining (PM) fiber in the pump source further improve and maintain linewidth in commercial applications.

A source of pump radiation, e.g. a single-mode or multi-mode laser diode 22, illuminates fiber 12 at a wavelength, typically 915-990nm, within the absorption band 24 of triply ionized ytterbium which occurs from 800 to 1070 nm as illustrated in figure 2. Pumping of the doped multi-component glass populates the ytterbium upper level creating a population inversion. Spontaneous emission catalyzes the

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stimulated emission **26** of the ytterbium ions in the upper level over a range of 900nm to 1100 nm. The emission peak **28** occurs at a wavelength of approximately 975 nm.

Laser emission occurs when the total gain produced by stimulated emission overcomes the losses in the cavity. The gain profile of ytterbium and the geometry of the resonant cavity create preferential feedback so that laser emission only occurs at one or more discrete wavelengths. As shown in figure 3, an ultra-short cavity, less than 5cm and preferably less than 3cm, produces a mode spacing $\Delta\nu$ that is larger than the linewidth **30** of the narrowband grating (less than 0.07 nm), which together with the gain spectrum **31** limits laser emission to a single longitudinal mode **32**. The fiber laser outputs the single-mode signal **32** having a center wavelength between approximately 0.98 μm and 1.08 μm with a linewidth less than 10 kHz as shown in figure 4a. This single-frequency 1um laser has output power levels **34** in excess of 170 mW as shown in figure 4b using a 400 mW laser diode pump.

To achieve both single-frequency performance and high output power levels the glass host must support very high ytterbium doping concentrations to realize the necessary gain. Compared to either silica or phosphosilicate, oxide-based multi-component glass hosts selected from phosphate, germanate or tellurite improve the solubility to ytterbium ions thereby allowing higher dopant levels without forming ion-clusters.

The multi-component laser glass contains a network former (P_2O_5 phosphate-oxide, GeO_2 germanate-oxide or TeO_2 tellurite-oxide), one or more glass network modifiers MO (alkaline-earth oxides and transition metal oxides such as

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BaO, CaO, MgO, SrO, ZnO, PbO and mixtures thereof) and one or more glass network intermediators L_2O_3 (Y_2O_3, La_2O_3, Al_2O_3, B_2O_3 and mixtures thereof). The modifier modifies the phosphate's glass network, thereby reducing its melting temperature and creating additional dopant sites. The intermediator bridges some of the bonds in the network thereby increasing the network's strength and chemical durability without raising the melting temperature appreciably. The multi-component glasses of interest thus have a much lower softening temperature than silica (SiO_2), which greatly simplifies processing. The modified network provides many more sites for hosting high concentrations of ytterbium dopants without clustering problems.

In general, the network former is 30 to 80 weight percent, the modifier can be at least 5 % and typically 15% by weight and the intermediator can be at least 2 % and typically 10 % by weight of the multi-component glass. As shown in figure 5, the fiber core **40** is made up of the glass host doped with high concentrations of ytterbium. The cladding layer(s) **42** are typically undoped. Dopant levels range from 0.5-30 wt. % ytterbium ions with typical values of 3-20 wt. %. Initial experiments have demonstrated that this class of phosphate glass supports continuous single-mode lasing without self-pulsation at high doping concentrations.

Numerous glass compositions were characterized for thermal properties (crystallization, expansion coefficient, transition and softening temperatures, core-to-clad similarity), chemical durability, ability to host high Yb doping concentrations without quenching, spectroscopic properties (maximum emission cross-section at 1.0 microns),

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linewidth (maximum breadth at 1.0 microns) and refractive index to determine a range of wt.% for each ingredient that are acceptable.

5 Example 1

No.1 Wt%	P2O5	Al2O3	La2O3	Yb2O3	BaO	B2O3	ZnO	Total
	63.30	4.33	0.31	2.00	27.68	1.23	1.15	100.00

Example 2

No.2 Wt%	P2O5	Al2O3	La2O3	Yb2O3	BaO	B2O3	ZnO	Total
	61.05	4.17	0.00	5.79	26.69	1.19	1.11	100.00

Example 3

No.3 Wt%	P2O5	Al2O3	La2O3	Yb2O3	BaO	B2O3	ZnO	Total
	59.62	4.07	0.00	8.00	26.06	1.16	1.08	99.99

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Example 4

No.4 Wt%	P2O5	Al2O3	La2O3	Yb2O3	BaO	B2O3	ZnO	Total
	56.65	3.87	0.00	12.57	24.77	1.10	1.03	99.99

Example 5

No.5 Wt%	P2O5	Al2O3	La2O3	Yb2O3	BaO	B2O3	ZnO	Total
	55.08	3.76	0.00	15.00	24.08	1.07	1.00	99.99

15   In another embodiment, the gain fiber **12** is a polarization maintaining (PM) fiber, which reduces the noise level in the laser and improves output power stability. As a result of their specific local environment, the active ions experience an anisotropy that leads to polarization

20 dependent gain, which means that the gain spectra for two different polarization components are not the same. Combining polarization selective feedback with a polarization maintaining active fiber reduces the low frequency noise that results from random polarization

fluctuations inside the laser cavity.

The subclass of multi-component glasses has a much
lower softening temperature (<600°C) than silica (>1200°C),
which greatly simplifies the fiber drawing process and
5 supports higher doping concentrations but complicates the
process of fusion splicing to silica fiber. A quality fusion
splice should exhibit low optical loss (< 0.3 dB), low back
reflection loss (< -50 dB) and good tensile strength (> 100
g). A standard silica-to-silica fusion splice degrades the
10 multi-component fiber. Instead an asymmetric process that
softens only the multi-component fiber is employed as
described in co-pending U.S. application Serial No.
09/963,727 entitled "Method of Fusion Splicing Silica Fiber
with Low-Temperature Multi-Component Glass Fiber" filed on
15 September 26, 2001, which is incorporated by reference. To
reduce back-reflection, an angle splicing process in which
the silica fiber is angle cleaved, the multi-component fiber
square cleaved and a matched angle formed in-situ may be
employed as described in co-pending U.S. application Serial
20 No. 10/374,001 entitled "Method of Angle Fusion Splicing
Silica Fiber with Low-Temperature Non-Silica Fiber" filed on
February 25, 2003 the entire contents of which are
incorporated by reference.

As shown in figures 6a and 6b, the single mode 1um
25 laser is placed inside a package 50 that provides thermal
and vibration isolation. The fiber chain 52 is placed in a
mounting fixture 54 having first and second thermally
isolated sections 56 and 58 for supporting the narrowband
and broadband fiber gratings 14 and 16 respectively. The
30 gain fiber is supported in either the first or second
section or in a third isolated section (not shown in this

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embodiment). Resistive heaters 60 thermistors 61 are mounted on the first and second sections and independently controlled to match the wavelengths of narrowband and broadband gratings.

5   The mounting fixture 54 is connected to the laser external package 50 through connectors 62 made of compliant material with relatively small Young modulus and a small thermal conductivity coefficient. The mounting fixture 54 containing the fiber chain and more specifically the first

10 and second thermally isolated sections 56 and 58 are independently heated above room temperature and temperature stabilized. The connection to the external package 50 with the compliant connectors 62 provides simultaneously good mechanical and thermal stability to the laser itself. This

15 is necessary for stable laser output.

As described above in connection with Figure 1, the optical cavity must be pumped to induce lasing. As shown in Figure 7, an off-the-shelf single-mode semiconductor pump diode 22 includes a semiconductor chip 70 and a grating 72

20 separated by about a meter of passive fiber 74. The grating locks the pump's output to a wavelength typically between 915nm and 990 nm. In most applications, the OTS pump diode is adequate. Since, however, very narrow linewidth lasers have a number of applications in sensing, in particular

25 acoustic sensing, it is important to ensure very low frequency and phase noise at low frequencies. The phase noise is particularly sensitive to polarization fluctuations in the pump fiber. Single mode semiconductor pump lasers emit highly polarized light. The polarization of the

30 pump light is, however, sensitive to birefringence fluctuations in the pump fiber if PM fiber is not employed.

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The fiber **74** that leads from the diode **70** to the fiber laser is typically longer than 1 m and any vibration and acoustic pickup in this fiber leads to small changes in the pump light polarization. Due to the anisotropy of the active ions, this leads to additional noise in the fiber laser output. The effect is more pronounced in the phase noise as in the intensity noise. Ronnekleiv has already pointed out that this vibration and pressure sensitivity could be largely reduced if one would use a depolarized pump source. ["Frequency and Intensity Noise of Single Frequency Fiber Bragg Grating Lasers", by Erlend Ronnekleiv, Optical Fiber Technology, 7, 206-235 (2001) - page 227, second paragraph]. Placing a depolarizer between the highly-polarized pump laser and the fiber laser is one way to reduce the acoustic pickup in the lead fiber.

Using polarization maintaining (PM) fiber **74** from the pump diode **70** to the fiber laser avoids the costly depolarizer and has the same effect. Due to the birefringence in polarization maintaining fiber, the polarization state of the pump light will not change when the fiber is subject to mechanical vibrations or acoustic pressure waves. The polarization whose stimulated emission cross section of the gain fiber is higher is aligned to the orientation of the operating polarization of the narrow-band fiber Bragg grating. Experiments have shown that using PM fiber in the pump lead greatly reduces the phase noise of the fiber laser output and the sensitivity to low frequency external noise.

While several illustrative embodiments of the invention have been shown and described, numerous variations and alternate embodiments will occur to those skilled in the

art. Such variations and alternate embodiments are contemplated, and can be made without departing from the spirit and scope of the invention as defined in the appended claims.

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